AUG 3 1982

Y3.T25:2 OC1

TVA/ONR/ARP-81/8

TENNESSEE VALLEY AUTHORITY

COMPLETED
62

ORIGINAL

THE OCCURRENCE OF ANTHROPOGENIC FOG AND ICE FROM WIDOWS CREEK UNIT 8 WET SCRUBBER

by

Jesse H. Coleman
LaRue C. Fagen

AIR RESOURCES PROGRAM

TVA/ONR/ARP-81/8

TENNESSEE VALLEY AUTHORITY

Office of Natural Resources

THE OCCURRENCE OF ANTHROPOGENIC FOG AND ICE FROM WIDOWS CREEK UNIT 8 WET SCRUBBER

Prepared by

Jesse H. Coleman and LaRue C. Fagen
Air Resources Program
Research Section
Muscle Shoals, Alabama

May 1981

I

EXECUTIVE SUMMARY

This report describes the results of a modeling study of the effect of the Widows Creek Steam Plant Unit 8 scrubbed plume upon ambient ice and fog formation within 20 km of the plant. The effect of the scrubber on reducing ambient SO_2 near the plant is also investigated. All investigations are repeated for three levels of scrubber reheat: high, medium, and low.

The level of plume reheat determines the final height of the scrubbed plume and strongly affects the concentration of water vapor at ground level. Thus, the level of plume reheat is strongly reflected in levels of anthropogenic fog and sulfur dioxide (SO_2) (i.e., environmental impact is always predicted to be greater at a low reheat level than at a high reheat level).

Very little impact of anthropogenic ice is predicted under any reheat level. At the worst case (lowest reheat), only 2 percent of the area around the Widows Creek Steam Plant is predicted to be impacted once per year and none of the area is predicted to be impacted twice or more.

Anthropogenic fog is predicted to have a low impact over a large area (55 percent of the area at one occurrence of fog per year, low reheat) and to have a higher impact over a small area (10 percent of the area at 10 occurrences of fog per year, low reheat).

BEST DOCUMENT AVAILABLE

It is assumed the scrubber removed 88 percent of the SO_2 in the plume. Because of reduced plume rise, however, ambient SO_2 concentrations are often not reduced by 88 percent. Under low reheat, for example, nearly 25 percent of the area near Widows Creek Steam Plant is predicted to experience a reduction in annual averaged SO_2 concentrations of less than 75 percent. Under medium reheat, however, this area of impact is reduced from 25 percent to less than 2 percent.

BEST DOCUMENT AVAILABLE

CONTENTS

	Page
Executive Summary	ii
Figures	v
Tables	vi
Introduction	1
Fog and Ice Occurrences	2
Results of the Analysis of Anthropogenic Fog	3
Results of the Analysis of Anthropogenic Ice	12
Ambient SO_2 Concentrations	12
Plume Observation Program	26
Conclusions	26
References	28
Appendices	
A. The model of anthropogenic fog and ice	29
B. The model of ambient SO_2 concentration reduction	35

FIGURES

Number		Page
1	Terrain higher than 250 m near Widows Creek Steam Plant	4
2	Isopleths of total occurrences of anthropogenic fog - high reheat	6
3	Isopleths of total occurrences of anthropogenic fog - medium reheat	7
4	Isopleths of total occurrences of anthropogenic fog - low reheat	8
5	Isopleths of occurrences of anthropogenic fog not occurring with ambient fog - high reheat	9
6	Isopleths of occurrences of anthropogenic fog not occurring with ambient fog - medium reheat	10
7	Isopleths of occurrences of anthropogenic fog not occurring with ambient fog - low reheat	11
8	Occurrences of ambient fog in 16 direction sectors	13
9	Isopleths of total occurrences of anthropogenic ice - low reheat	15
10	Isopleths of occurrences of anthropogenic ice not occurring with ambient ice - low reheat	16
11	Occurrences of ambient ice in 16 direction sectors	17
12	Efficiency of scrubber and altered dispersion in reducing maximum SO_2 concentrations - maximum reheat	19
13	Efficiency of scrubber and altered dispersion in reducing maximum SO_2 concentrations - medium reheat	20
14	Efficiency of scrubber and altered dispersion in reducing maximum SO_2 concentrations - low reheat	21
15	Efficiency of scrubber and altered dispersion in reducing annual average SO_2 concentrations - maximum reheat	22
16	Efficiency of scrubber and altered dispersion in reducing annual average SO_2 concentrations - medium reheat	23
17	Efficiency of scrubber and altered dispersion in reducing annual average SO_2 concentrations - low reheat	24

TABLES

Number		Page
1	Area Affected by Anthropogenic Fog from Widows Creek Unit 8 Scrubbed Plume and its Association with Ambient Fog	5
2	Area Affected by Anthropogenic Ice from Widows Creek Unit 8 Scrubbed Plume and its Association with Ambient Ice	14
3	Fractions of the Total Area Within 20 km of Widows Creek Steam Plant Experiencing Varying SO_2 Reduction Levels Due to the Combination of Unit 8 Scrubber and Reduced Dispersion	18
A.1	Meteorological Conditions used in Plume Rise Calculations	31
A.2	Stack Exit Gas Condition Representing Different Reheat Levels	31

INTRODUCTION

This report describes a theoretical analysis of the possible increased frequency of anthropogenic fog and ice due to the operation of Widows Creek Unit 8 wet limestone scrubber. Also analyzed are changes in ambient SO_2 concentrations from Unit 8 due to its scrubber. The effect of different stack gas reheat is emphasized in both analyses. This report is prepared as part of Subtasks 6.1 and 6.2 of the TVA Widows Creek Unit 8 Wet Limestone Scrubber Research Project. The main part of the report describes the results of the modeling study at different reheat values. Details of the dispersion models are reported in appendices. Also described briefly is a program of routine observations of the condensed plume from the Widows Creek Unit 8 scrubber.

The plume from a coal-fired power plant using wet scrubbing is nearly saturated with water vapor. Thus, the scrubbed plume is a relatively large source of moisture that may increase the frequency of fog and ice in the region surrounding the power plant. Because of this, the possibility of increased fog and ice due to the operation of Widows Creek Unit 8 wet scrubber was investigated.

A theoretical model and an observational program to collect data on the actual frequency of condensed plumes from the scrubber are the two parts of this investigation. This report concerns the theoretical analysis and its results. The plume observation program is underway at the time this report is being prepared. The results of the observational program will be presented in an upcoming report.

FOG AND ICE OCCURRENCES

The model developed to estimate occurrences of anthropogenic ice and fog is a synthesis of existing plume rise and dispersion models that are described in Appendix A.

The procedure for modeling anthropogenic fog and ice produces a vast amount of computer generated data. The data are summarized in tables and presented graphically as isopleths of occurrence frequency. All data plotted as isopleths have been smoothed to remove extraneous lines and to make areas of potential fog and ice impact more easily recognizable.

The exact conditions under which fog or ice forms are not well described by routine meteorological data. Complicating factors include the effect of varying types and concentrations of condensation nuclei, the varying radiative cooling behavior of different surfaces, and the complex processes involved in the vertical transfer of atmospheric heat and moisture. For the purpose of this analysis, the following is assumed: (1) fog will form when atmospheric relative humidity equals or exceeds 100 percent, and (2) ice will form when atmospheric relative humidity exceeds 100 percent and the atmospheric temperature is below freezing. These assumptions are reasonable and permit an accurate assessment of the impact of the scrubbed plume and the effect of varying plume reheat.

Since this computer modeling study is based on monitored meteorological data, errors in meteorological data will affect the results. Small random and systematic errors that are almost always present in

routine measurements of dry-bulb and dewpoint temperatures are usually not important in many studies using monitoring data. However, in the ice and fog analyses the difference between the dry-bulb and dewpoint temperatures when they are nearly equal is extremely important. When the relative humidity is near 100 percent, the dewpoint temperature almost equals the dry-bulb temperature. In this region of the data, the significance of errors increases. While the exact effects of these errors on the results of this analysis have not been assessed, the meteorological monitoring system at Widows Creek is well designed and maintained and thus the final results are as accurate as possible. Terrain near the Widows Creek Steam Plant is illustrated in Figure 1. These terrain features strongly affect the results of this analysis.

RESULTS OF THE ANALYSIS OF ANTHROPOGENIC FOG

Results of the analysis of anthropogenic fog are summarized in Table 1 and presented in more detail in Figures 2 through 7. According to the assumptions made here, under a medium reheat level anthropogenic fog would occur at least once per year over 52.6 percent of the area within 20 km of the plant. Fog would also occur five times or more over 20.3 percent of the area, Under medium reheat, most fog occurs on the high terrain points northwest of the plant with a secondary impact point to the northeast (Figure 3). The impact locations of anthropogenic fog reflect the influence of the moist air in southerly flows (Figures 2 through 7). Plume impact increases with decreasing plume reheat (Table 1 and Figures 2 through 7). Most anthropogenic fog occurs when ambient fog is not occurring (Table 1).

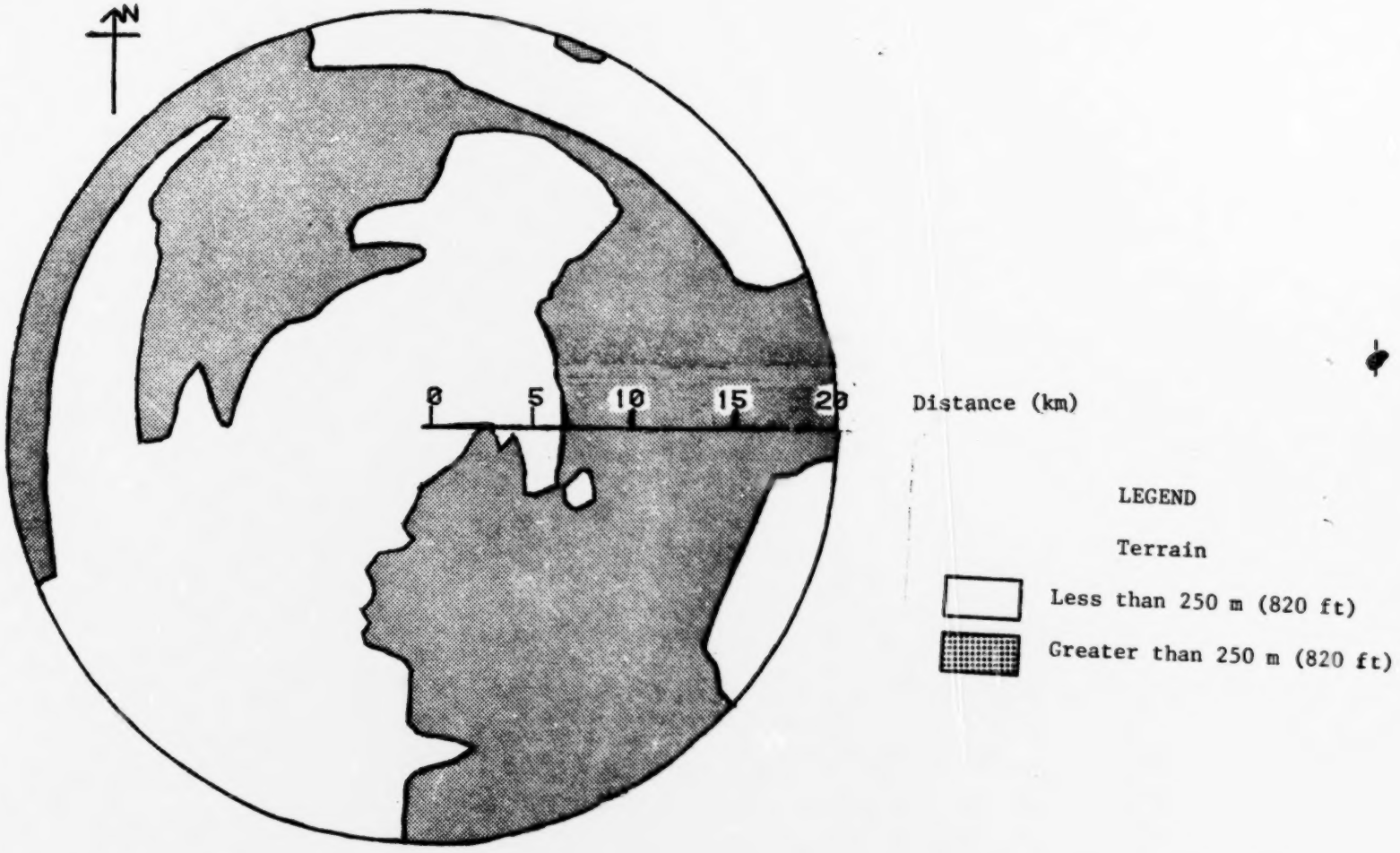

Figure 1. Terrain higher than 250 m near Widows Creek Steam Plant.

BEST DOCUMENT AVAILABLE

Table 1

AREA AFFECTED BY ANTHROPOGENIC FOG FROM WIDOWS CREEK UNIT 8 SCRUBBED PLUME AND ITS ASSOCIATION WITH AMBIENT FOG

Reheat level	Area Affected by Fog (%)*		
	1 occurrence/year	5 occurrences/year	10 occurrences/year**
	Anthropogenic Fog Not Occurring with Ambient Fog		
High	41.0	10.8	0.2
Medium	48.6	15.1	0.2
Low	51.8	19.5	0.6
	Anthropogenic Fog Occurring with Ambient Fog		
High	21.5	0.0	0.0
Medium	26.3	0.0	0.0
Low	36.1	0.0	0.0
	Total Occurrences of Anthropogenic Fog		
High	50.4	15.5	4.4
Medium	52.6	20.3	6.4
Low	55.0	24.5	10.0

*Total area analyzed was 498 square miles.
**Occurrence levels refer to minimum levels: 1 occurrence or more/year, etc.

BEST DOCUMENT AVAILABLE

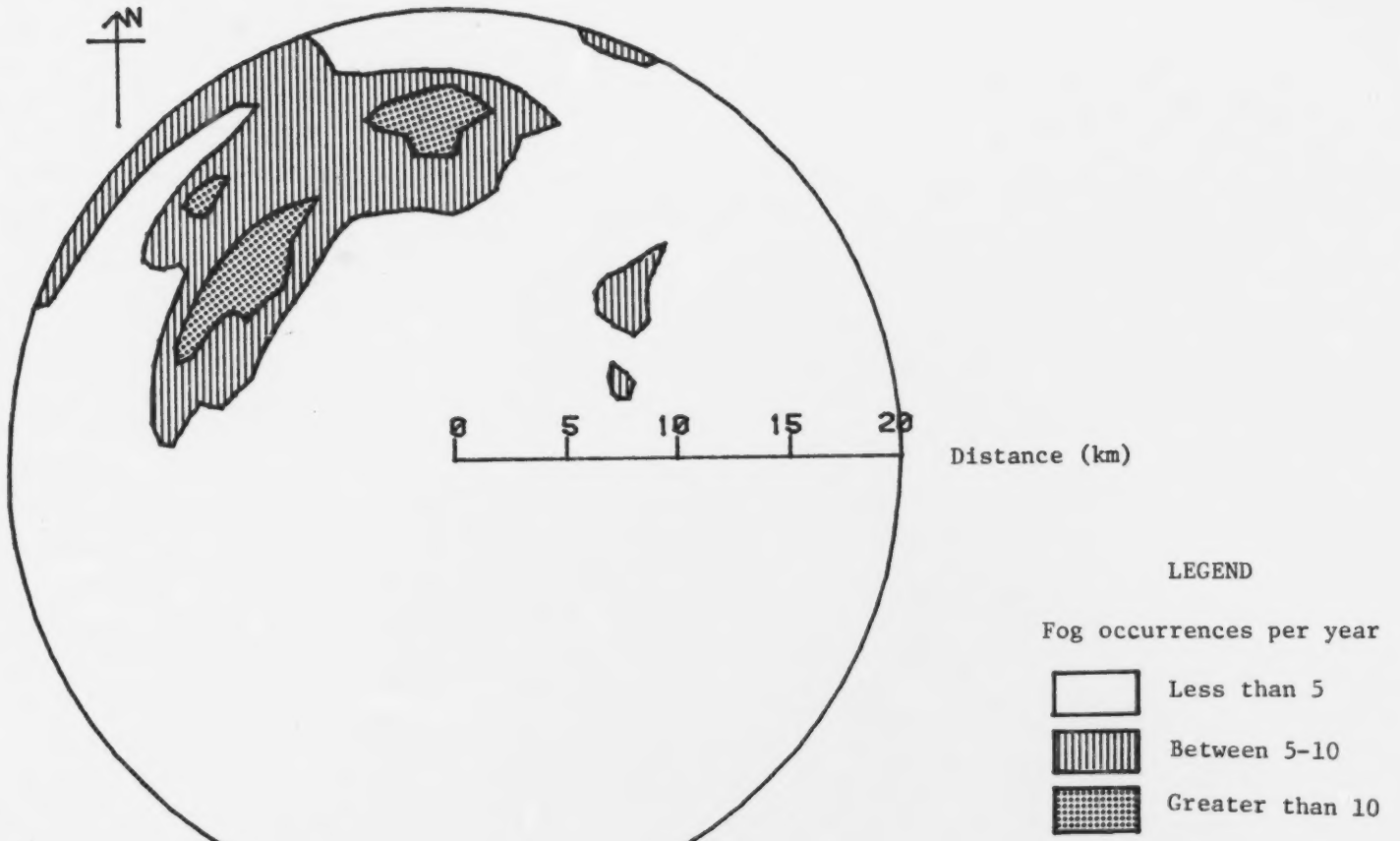

Figure 2. Isopleths of total occurrences of anthropogenic fog - high reheat.

BEST DOCUMENT AVAILABLE

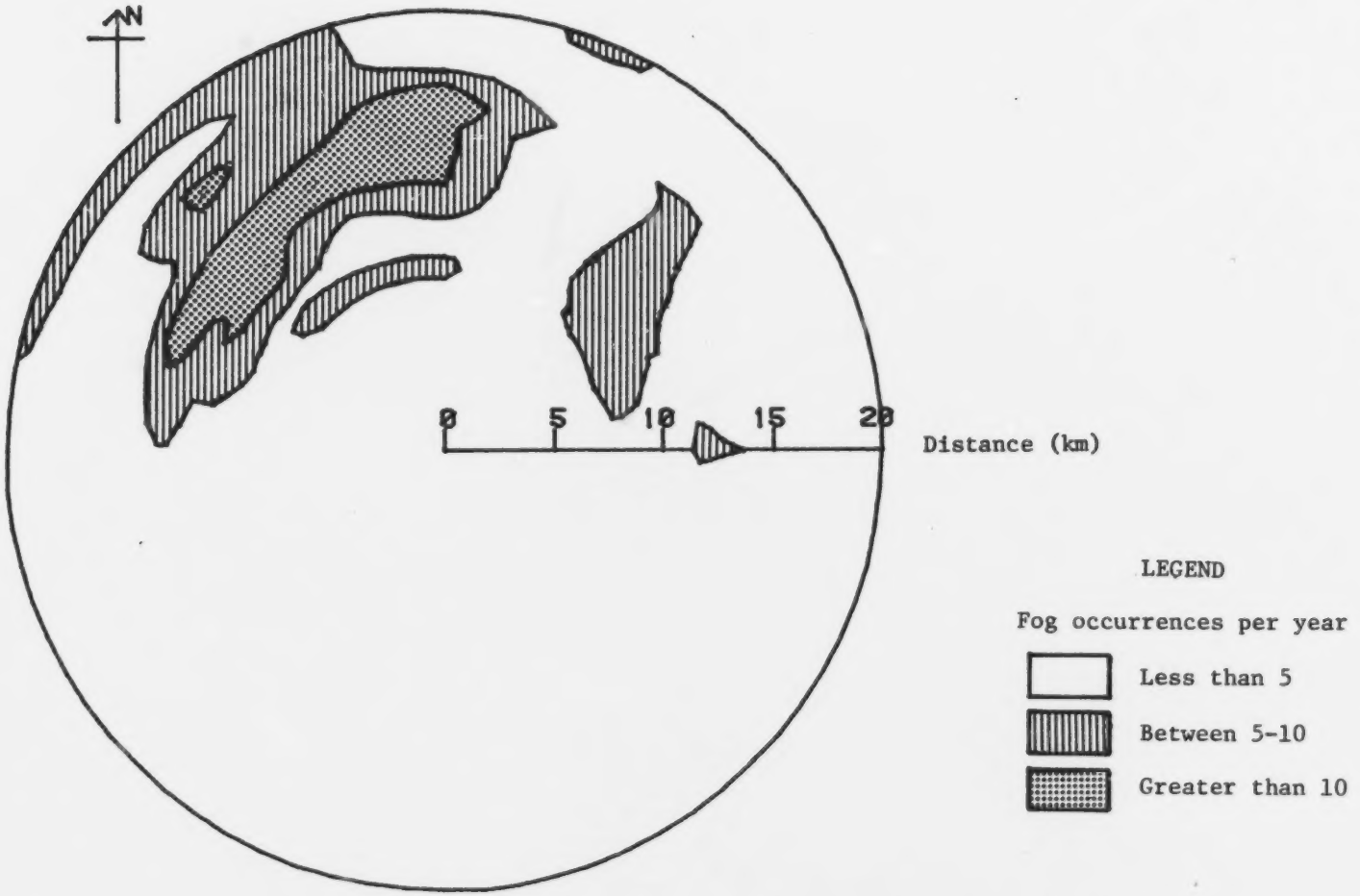

Figure 3. Isopleths of total occurrences of anthropogenic fog - medium reheat.

BEST DOCUMENT AVAILABLE

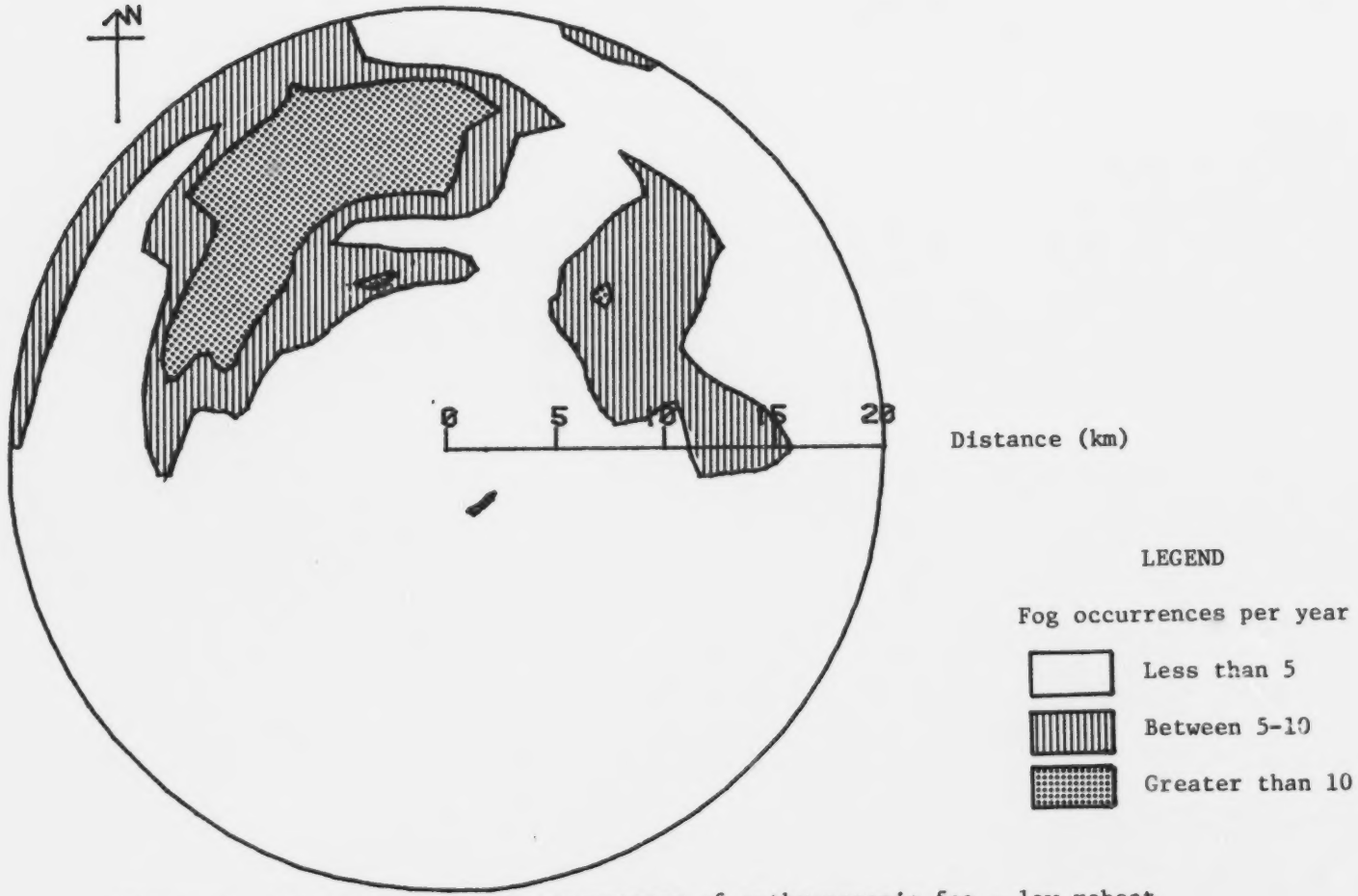

Figure 4. Isopleths of total occurrences of anthropogenic fog - low reheat.

BEST DOCUMENT AVAILABLE

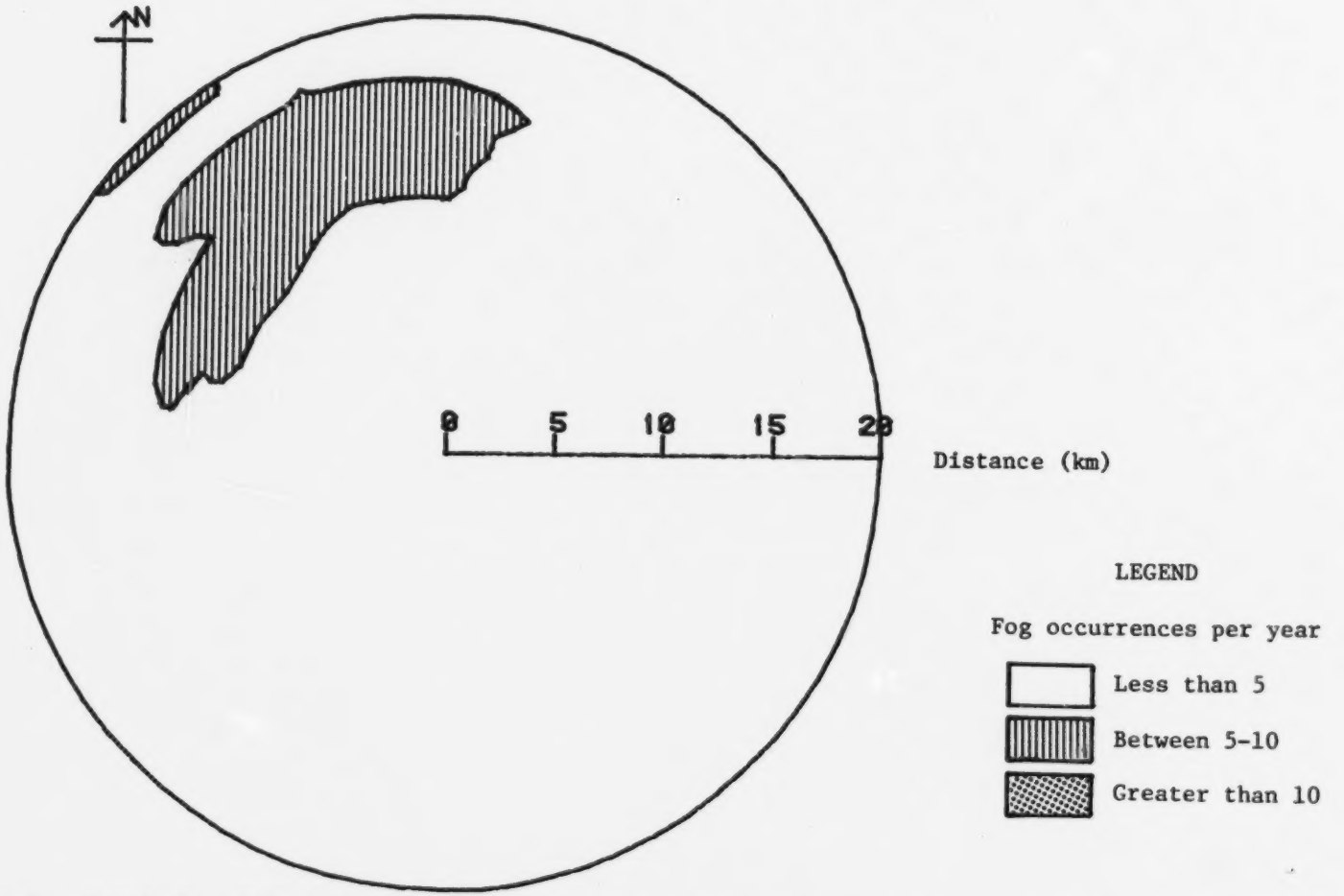

Figure 5. Isopleths of occurrences of anthropogenic fog not occurring with ambient fog - high reheat.

BEST DOCUMENT AVAILABLE

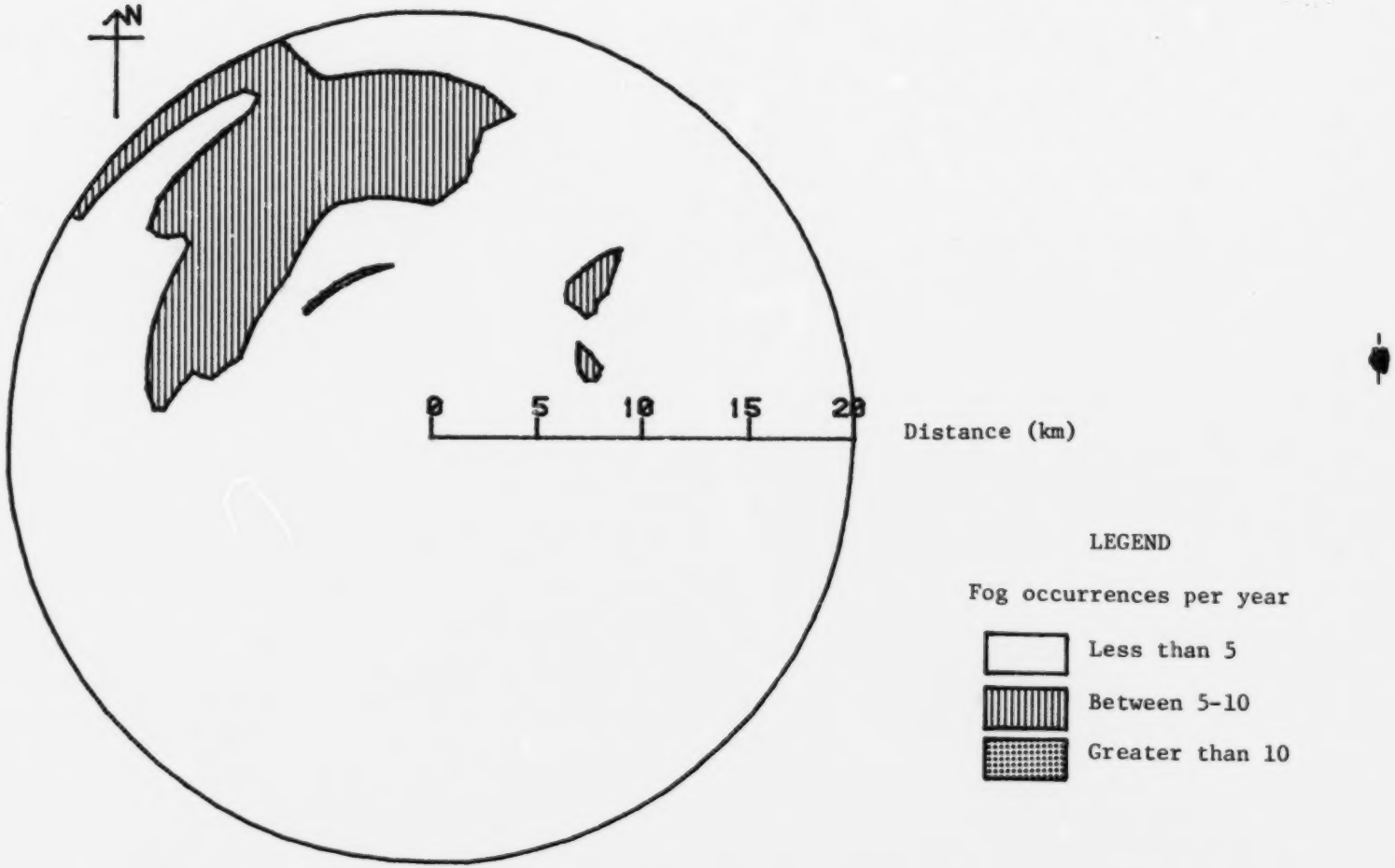

Figure 6. Isopleths of occurrences of anthropogenic fog not occurring with ambient fog - medium reheat.

BEST DOCUMENT AVAILABLE

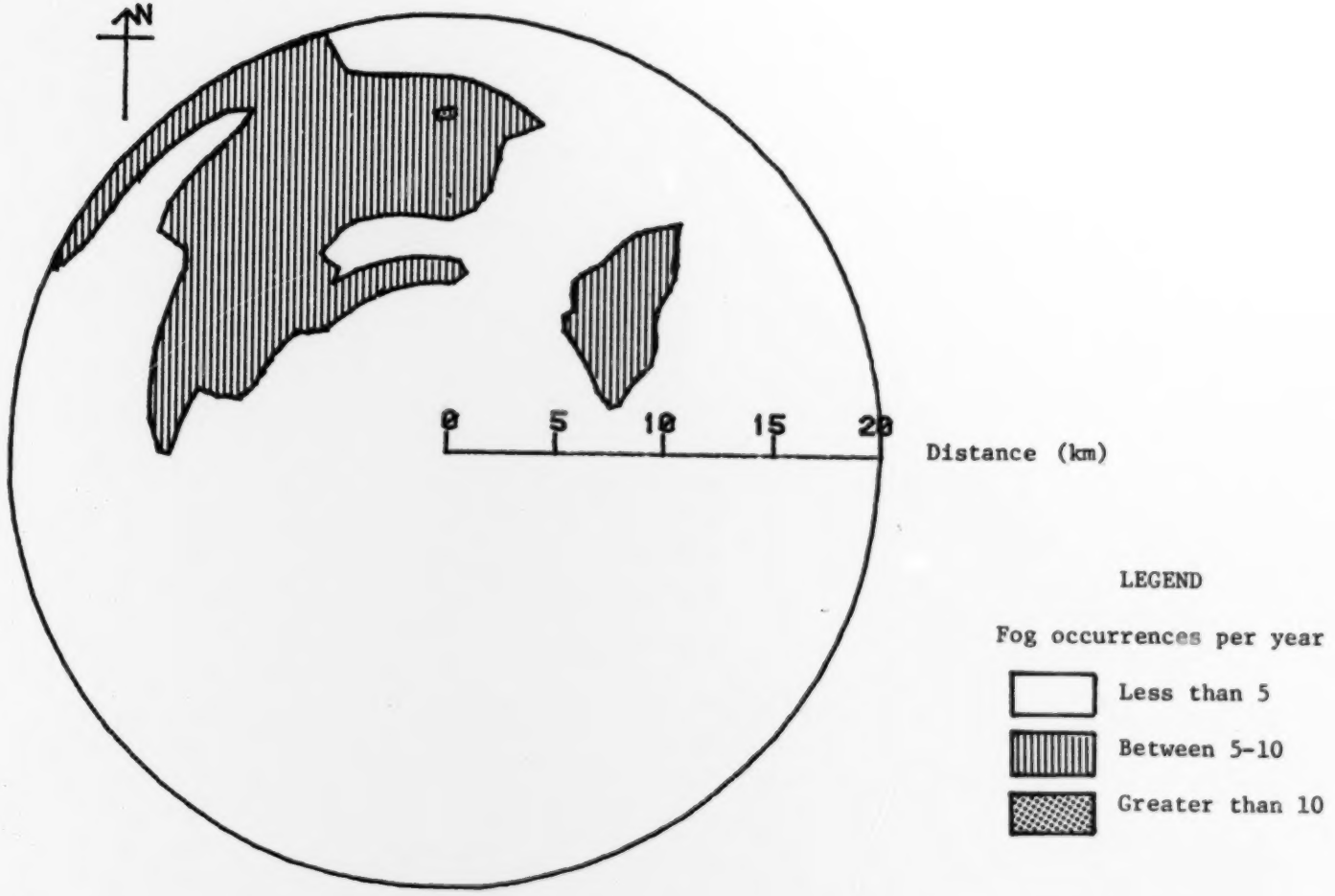

Figure 7. Isopleths of occurrences of anthropogenic fog not occurring with ambient fog - low reheat.

// BEST DOCUMENT AVAILABLE

According to these fog occurrence criteria, ambient fog occurs about 260 times a year. Ambient fog may occur when the wind is from any direction but is more likely with southerly or southwesterly winds (Figure 8). These are the same wind directions that produced the most significant anthropogenic fog impacts. Calculated ambient fog events lasted about two hours and anthropogenic fog events lasted about one hour.

RESULTS OF THE ANALYSIS OF ANTHROPOGENIC ICE

The data summarized in Table 2 shows the anthropogenic ice analysis. According to the assumptions of this analysis, under a medium reheat level anthropogenic ice would occur at least one or more times during a one-year period over only 0.6 percent of the area. Anthropogenic ice, when it occurs, is expected on small areas SE and NE of the plant on Sand Mountain (Table 2 and Figures 9 and 10). An average calculated ambient ice event would last about two hours and an average anthropogenic ice event would last about one hour. According to the criteria of this model, ambient ice would occur about 21 times in the Widows Creek area and result, as expected, primarily from northwesterly winds. Ambient ice condition data are summarized in Figure 11.

AMBIENT SO_2 CONCENTRATIONS

The model used to estimate ambient SO_2 concentrations from Widows Creek Unit 8 scrubbed plume is described in Appendix B.

The results of this modeling analysis, like that for anthropogenic fog and ice, produce a vast amount of computer data. These data are summarized in Table 3 and Figures 12 through 17. It is assumed that

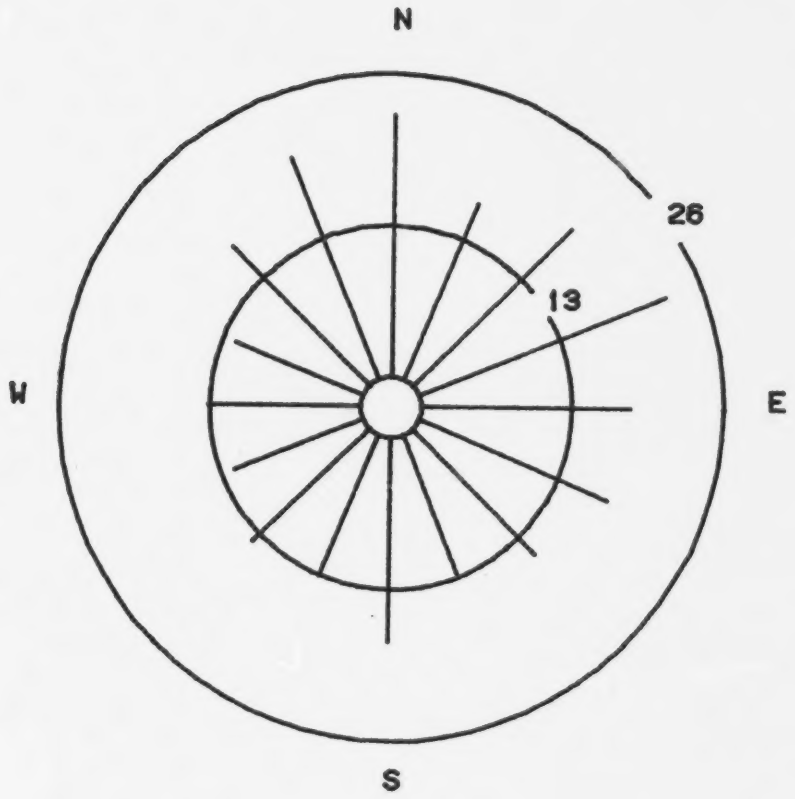

Figure 8. Occurrences of ambient fog in 16 direction sectors.

BEST DOCUMENT AVAILABLE

Table 2

AREA AFFECTED BY ANTHROPOGENIC ICE FROM WIDOWS CREEK UNIT 8 SCRUBBED PLUME AND ITS ASSOCIATION WITH AMBIENT ICE

Reheat Level	Area Affected by Ice (%)*	
	1 occurrence/year	2 occurrences/year
Anthropogenic Ice not Occurring with Ambient Ice		
High	0.0	0.0
Medium	0.0	0.0
Low	0.6	0.0
Anthropogenic Ice Occurring with Ambient Ice		
High	0.0	0.0
Medium	0.0	0.0
Low	0.0	0.0
Total Occurrences of Anthropogenic Ice		
High	0.4	0.0
Medium	0.6	0.0
Low	2.0	0.0

*Total area analyzed was 498 square miles.

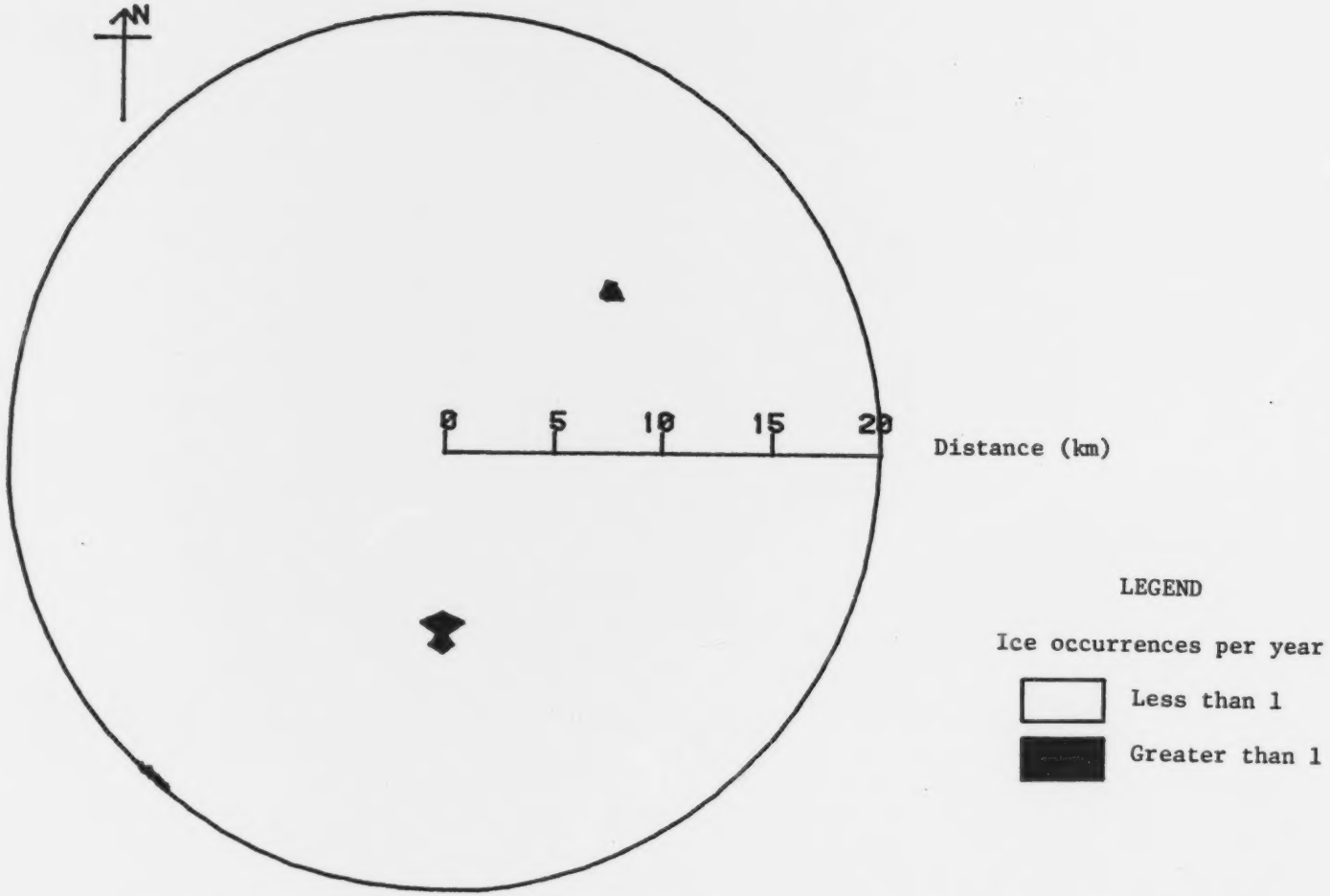

Figure 9. Isopleths of total occurrences of anthropogenic ice - low reheat.

BEST DOCUMENT AVAILABLE

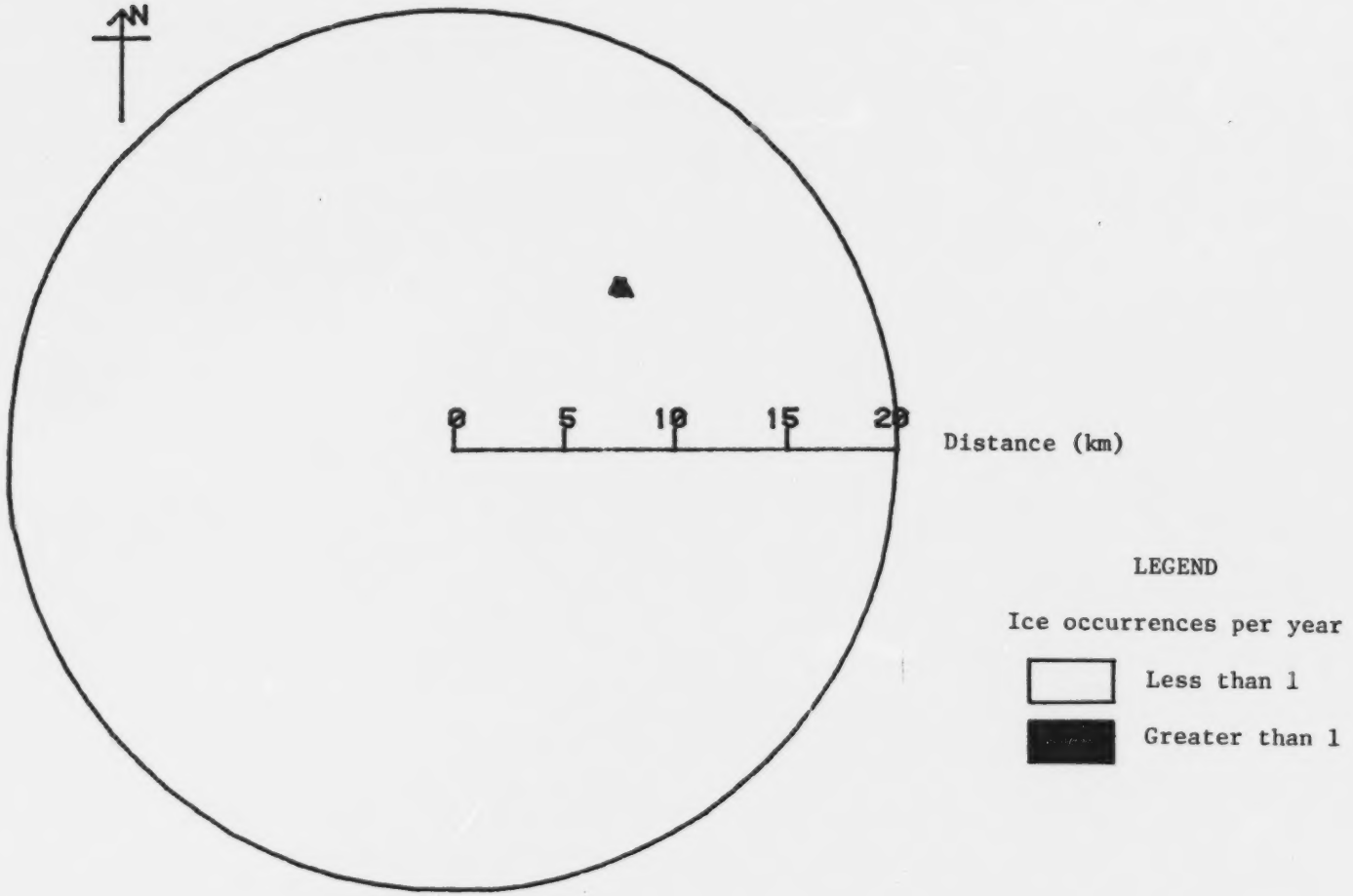

Figure 10. Isopleths of occurrences of anthropogenic ice not occurring with ambient ice - low reheat.

BEST DOCUMENT AVAILABLE

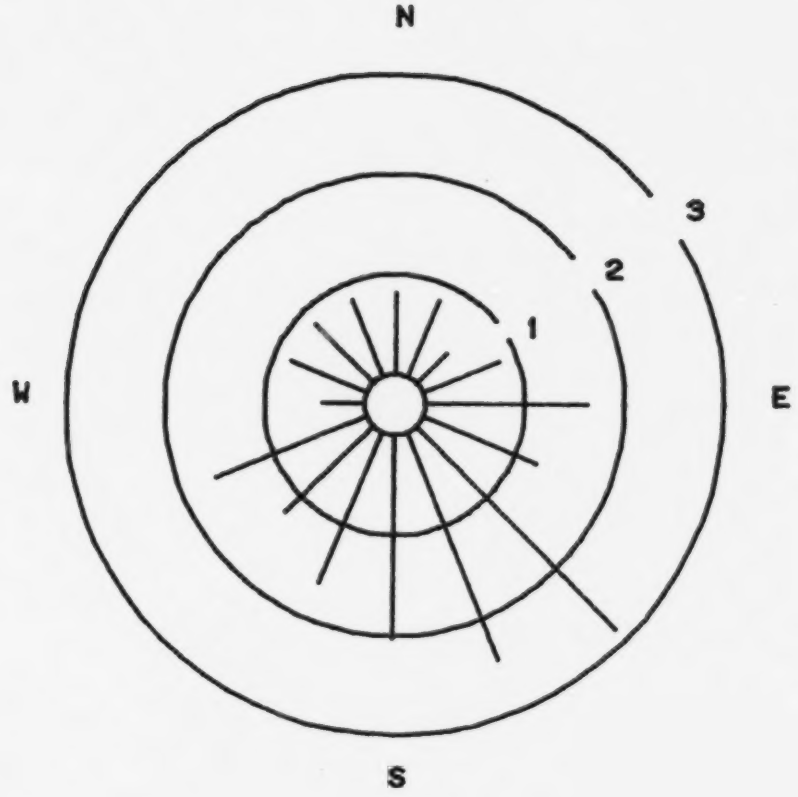

Figure 11. Occurrences of ambient ice in 16 direction sectors.

BEST DOCUMENT AVAILABLE

Table 3

PERCENTAGES OF THE TOTAL AREA WITHIN 20 KM OF WIDOWS CREEK STEAM PLANT EXPERIENCING VARYING SO_2 REDUCTION LEVELS DUE TO THE COMBINATION OF UNIT 8 SCRUBBER AND REDUCED DISPERSION

	Total Area (%)			
Reheat Level	Reduction of Annual Average SO_2 Concentration			
	<65%	65-75%	75-85%	>85%
High	0.0	0.0	20.5	79.5
Medium	0.2	1.6	46.0	52.2
Low	4.0	20.6	36.5	38.9

	Reduction of Maximum SO_2 Concentration			
	<65%	65-75%	75-85%	>85%
High	0.0	0.0	54.2	45.8
Medium	0.0	1.8	72.3	25.9
Low	5.8	38.1	40.8	15.3

BEST DOCUMENT AVAILABLE

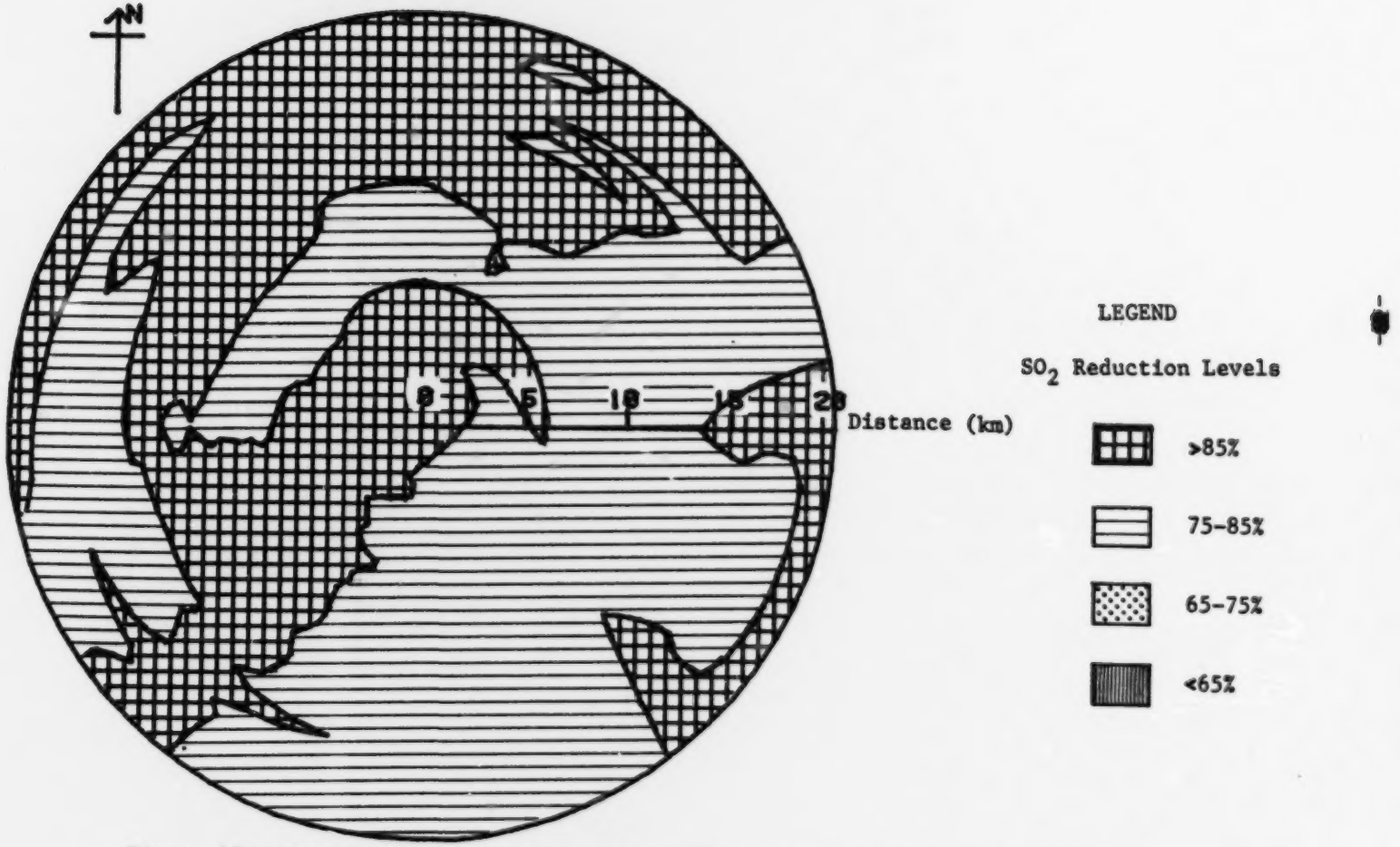

Figure 12. Efficiency of scrubber and altered dispersion in reducing maximum SO_2 concentrations - maximum reheat.

BEST DOCUMENT AVAILABLE

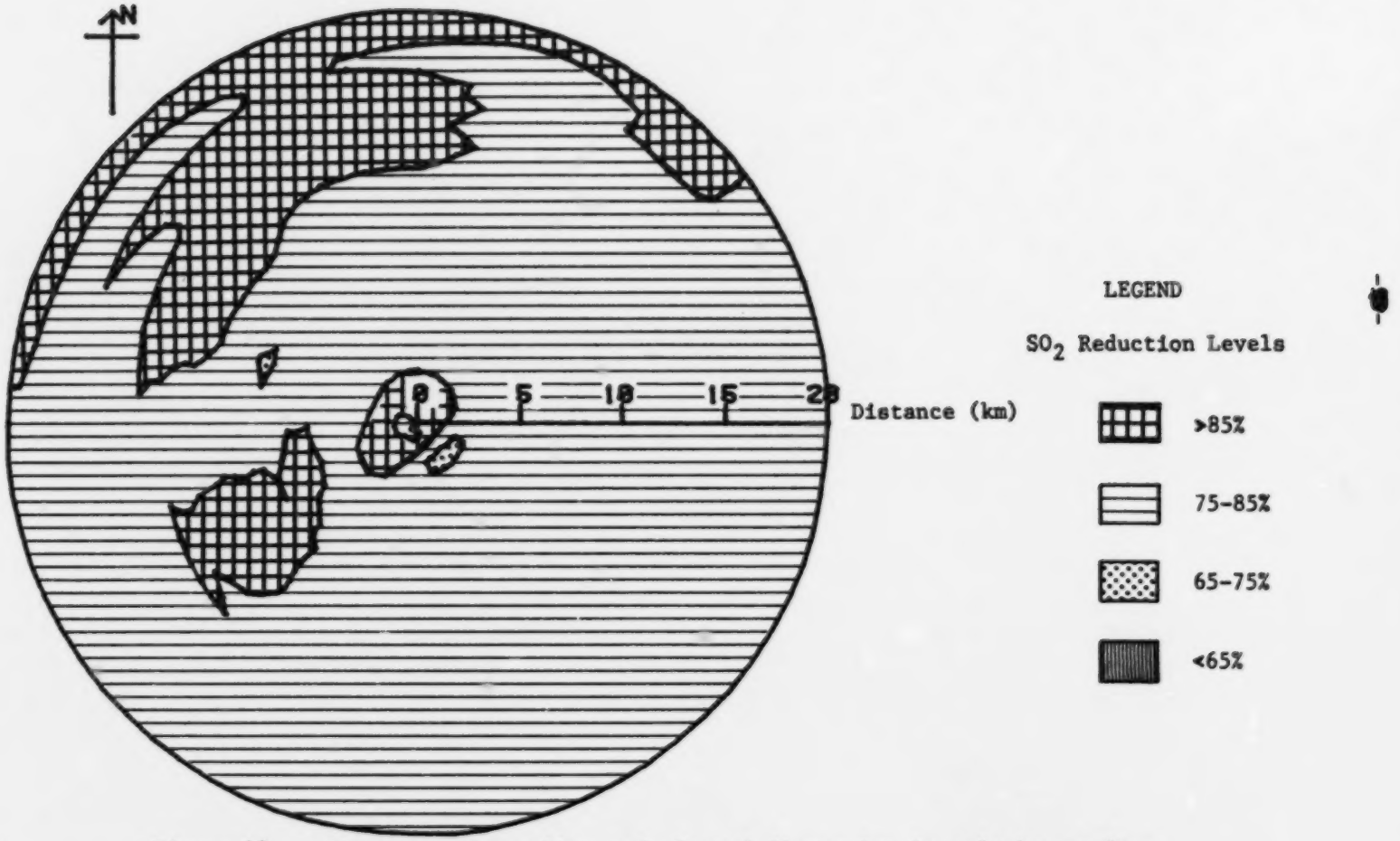

Figure 13. Efficiency of scrubber and altered dispersion in reducing maximum SO_2 concentrations - medium reheat.

BEST DOCUMENT AVAILABLE

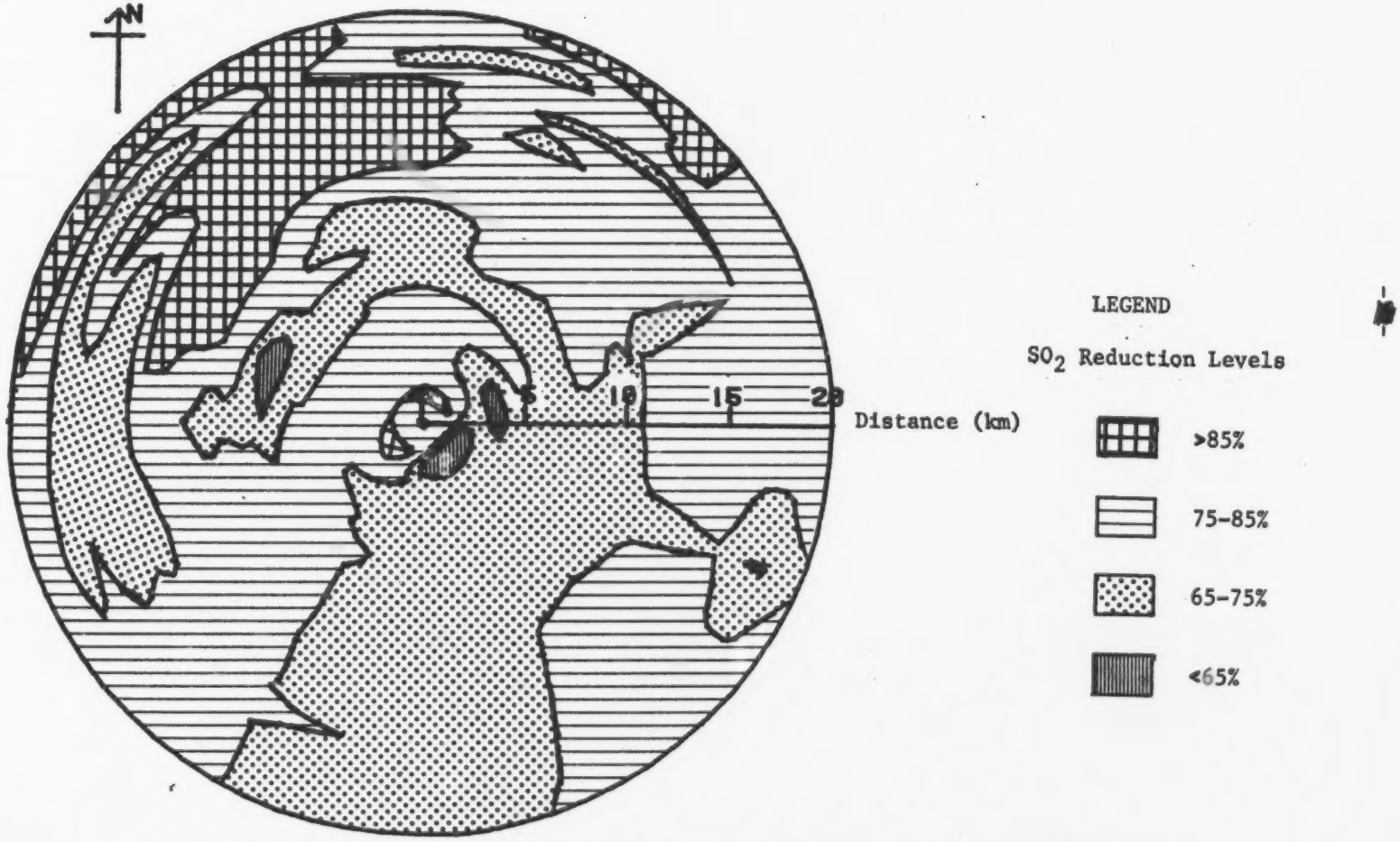

Figure 14. Efficiency of scrubber and altered dispersion in reducing maximum SO_2 concentrations - low reheat.

BEST DOCUMENT AVAILABLE

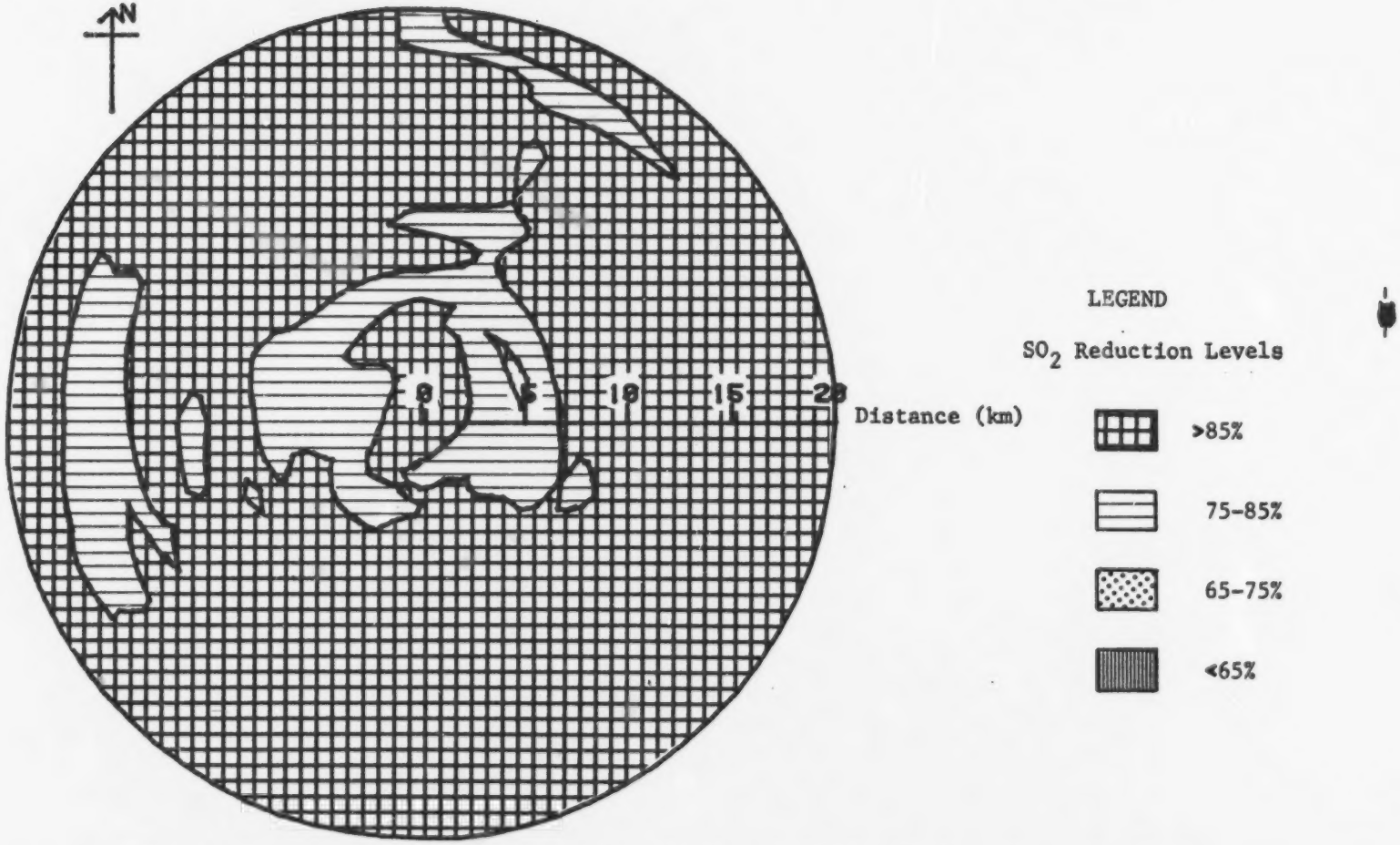

Figure 15. Efficiency of scrubber and altered dispersion in reducing annual average SO_2 concentrations - maximum reheat.

BEST DOCUMENT AVAILABLE

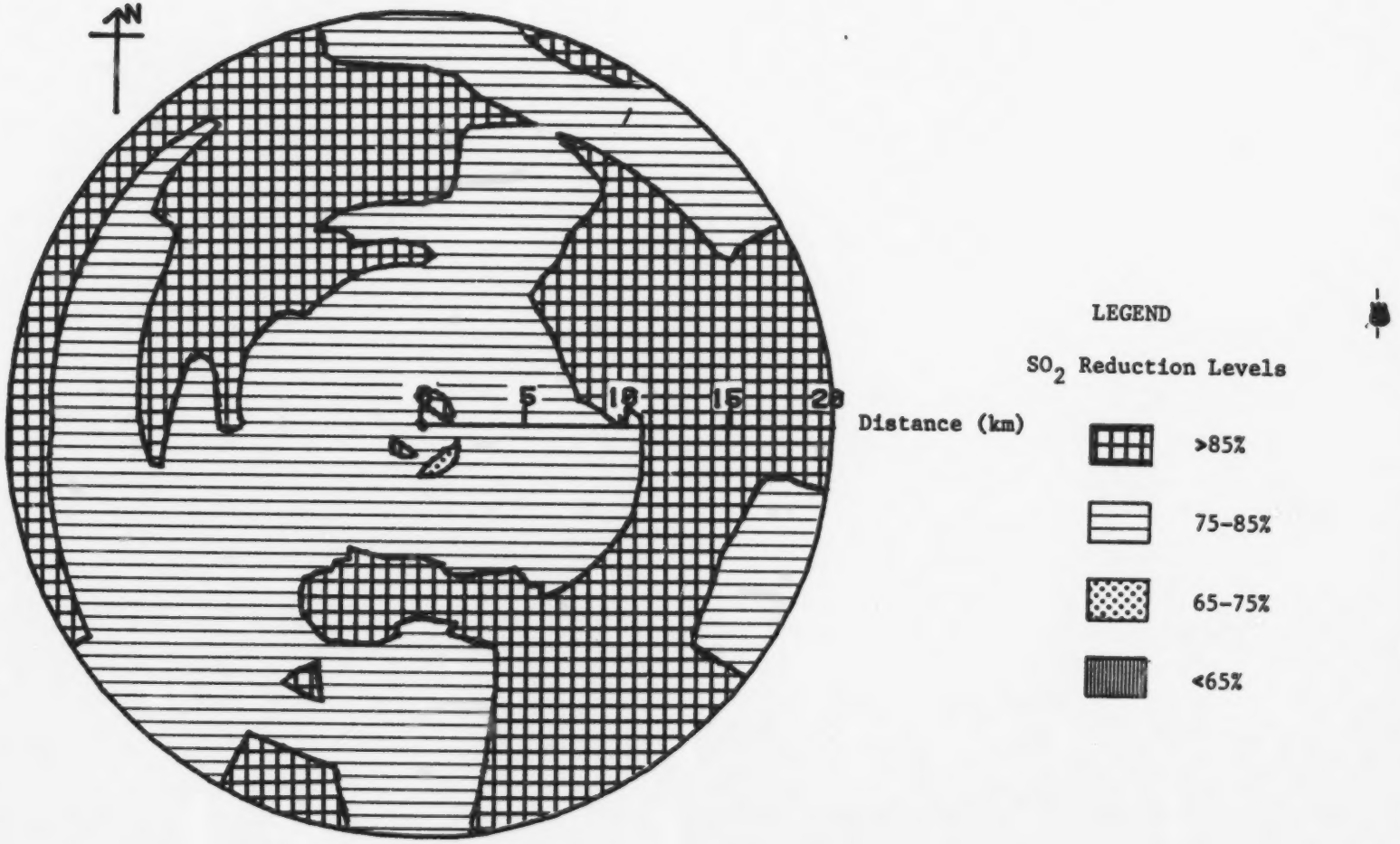

Figure 16. Efficiency of scrubber and altered dispersion in reducing annual average SO_2 concentrations - medium reheat.

BEST DOCUMENT AVAILABLE

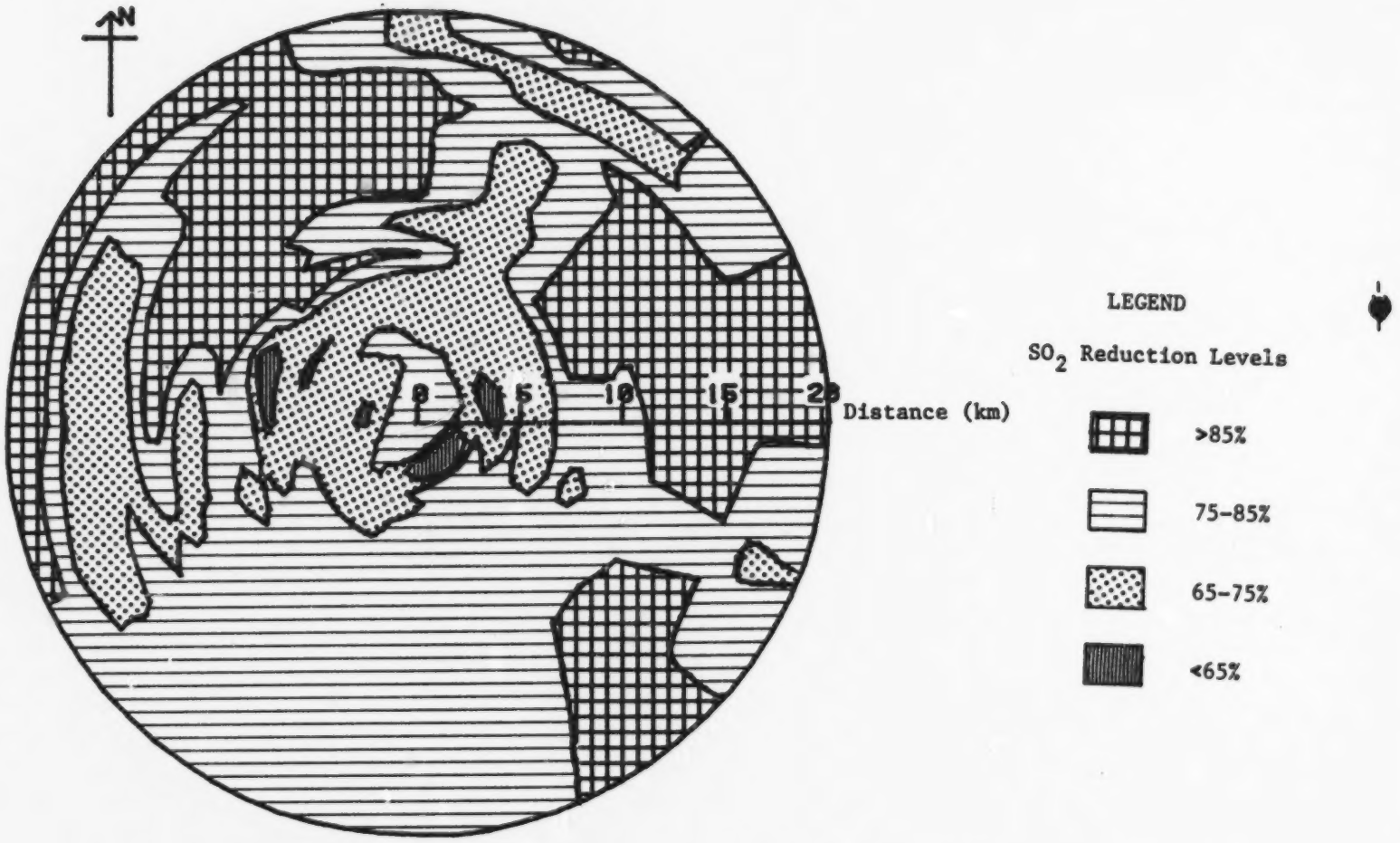

Figure 17. Efficiency of scrubber and altered dispersion in reducing annual average SO_2 concentrations - low reheat.

BEST DOCUMENT AVAILABLE

the scrubber reduces SO_2 emissions by 88 percent and that ambient concentration is a direct function of emissions. If plume rise is not affected by the scrubber, then all ambient SO_2 concentrations from Unit 8 would be reduced by 88 percent. However, the scrubbed plume is cooler and thus plume rise is reduced. Since the plume is lower, its ambient SO_2 concentrations per unit emission are higher and the efficiency of the scrubber in reducing ambient concentrations is reduced below 88 percent.

As illustrated in Table 3, the scrubber is more effective in reducing annual average SO_2 concentrations than in reducing maximum concentrations. The pronounced effect of variations in reheat level on reducing ground level concentrations is shown in Table 3. For example, with a high reheat level, 79.5 percent of the area near Widows Creek experiences a reduction in annual average SO_2 concentration of 85 percent or greater. With medium reheat, 52.2 percent of the area experiences this degree of reduction. With a low reheat level, only 38.9 percent of the area experiences this degree of reduction.

The modeled effects of reheat are more pronounced when lower levels of SO_2 reduction are examined. For example, under high reheat all of the area within 20 km of Widows Creek Steam Plant experiences at least a 75 percent reduction in annual average SO_2 concentration from Unit 8. However, at a low reheat level, 24.6 percent of the area experiences this reduced level of SO_2 concentrations.

Figures 12 through 17 illustrate that the efficiency of the scrubber in reducing ambient SO_2 concentrations is lowest at the high elevation points, particularly at those high elevations close to the plant.

PLUME OBSERVATION PROGRAM

As part of TVA's sulfur dioxide emission limitation program (SDEL), a staff of meteorological observers are on site at the Widows Creek Steam Plant 24 hours per day. Four temperature soundings are taken daily (weather permitting) by contract aircraft or radiosonde. These circumstances provide an excellent opportunity for observing the plume and thus for supplementing theoretical estimates with data on the actual occurrence of anthropogenic fog from Widows Creek Unit 8 scrubber. For this reason, an observational program was implemented at the Widows Creek SDEL station during late summer 1979. Four observations are taken daily by the temperature sounding aircraft pilot or by an on-site SDEL observer when flights are not taken. These observations consist of the length and height of a condensed plume from Unit 8, and meteorological and plant operational data.

When a complete year of data has been collected, the data will be analyzed and reported in a supplement to this report.

CONCLUSIONS

The modeled impact of the Widows Creek Unit 8 scrubbed plume is a function of plume reheat. The impact of the plume increases with decreasing reheat. This trend is seen in each of three analyses: anthropogenic fog and ice and also SO_2 reduction levels.

The impacts of anthropogenic fog and ice, as well as SO_2 emissions, are expected to be greatest in high terrain areas. The impact of

anthropogenic fog and ice is expected to be quite small. A relatively large area around Widows Creek is expected to be lightly impacted by anthropogenic fog but only a relatively small area is expected to be impacted as often as 10 times per year. In addition, the duration of these impacts will average only one hour per episode. The impact of anthropogenic ice is expected to be negligible with only a very small area being affected as often as once per year and no area impacted twice or more per year.

Because the scrubbed plume is not as buoyant as the unscrubbed plume, the efficiency of the scrubber in reducing ambient SO_2 concentrations is below the expected 88 percent.

REFERENCES

1. Slawson, P. R., J. H. Coleman, and J. W. Frey. Natural Draft Cooling Tower Plume Behavior at Paradise Steam Plant (Part II). TVA/EP-78/01, Tennessee Valley Authority, Chattanooga, Tennessee, February 1978.

2. Environmental Protection Agency. User's Network for Applied Modeling of Air Pollution (UNAMAP), NTIS PB 229771, National Technical Information Service, Springfield, Virginia (1974).

APPENDIX A

THE MODEL OF ANTHROPOGENIC FOG AND ICE

THE MODEL OF ANTHROPOGENIC FOG AND ICE

The model used to analyze anthropogenic fog and ice is a hybrid of two existing models. The first model portion, plume rise, is taken from the cooling tower plume model described by Slawson et al. (1) in which the rise of a buoyant, moist plume and its dilution due to self-generated turbulence is described. The second portion, plume dispersion, is taken from the Point/Distance (PTDIS) model developed by the Environmental Protection Agency (EPA) and described in the Handbook for UNAMAP (2). This model is routinely used to predict the ground-level concentration of a conservative atmospheric emission from a buoyant point source.

PLUME RISE PORTION

Final plume height, radius, and distance downwind are computed for 125 different meteorological conditions consisting of five relative humidities, five temperatures, and five different wind speeds. The values of these meteorological parameters are chosen to give the best resolution to those meteorological conditions that are most favorable to fog and ice formation--low wind speeds, low temperatures, and high relative humidities. The values chosen are shown in Table A.1. These meteorological data were collected at the Sand Mountain meteorological tower during 1977. Temperature and relative humidity were measured at 1 m and wind speed at 61 m on the tower.

The input data for this portion of the model also include stack exit conditions--the gas temperature, velocity, and humidity mixing ratio. Three sets of stack conditions representing different reheats at

Table A.1.

METEOROLOGICAL CONDITIONS USED IN PLUME RISE CALCULATIONS

Wind speed (mph)	Temperature (°F)	Relative humidity (%)
4.0	20	80.0
5.5	32	89.0
6.5	40	95.0
8.0	50	97.5
11.0	65	99.5

Table A.2.

STACK EXIT GAS CONDITIONS REPRESENTING DIFFERENT REHEAT LEVELS

Reheat level	Temperature (°C)	Exit velocity (m/sec)	Mixing ratio (lb water/lb dry gas)
High	79.44	22.8	.0656
Medium	65.56	21.9	.0656
Low	51.67	21.0	.0656

BEST DOCUMENT AVAILABLE

full load are used (Table A.2). An entrainment constant of 0.3 and a constant atmospheric pressure at the stack top of p = 1007.8 mb are used in the calculations.

PLUME DISPERSION PORTION

The dispersion portion uses a standard Gaussian model with Pasquill-Gifford stabilities A through F based on the temperature lapse rate between two levels on the meteorological tower. An inversion height of 1000 m is assumed in all calculations. The other meteorological input data are hourly ambient temperature, wind speed, wind direction, relative humidity, and temperature lapse rate.

The standard PTDIS model is modified to include a simple method for considering terrain. Terrain elevation is read from topographic maps for 16 wind sectors in 0.5 km steps up to 20 km (12.4 miles). The highest terrain point within each sector and 0.25 km of each point is recorded as the elevation at that point. This assumption, that the highest terrain point is representative of all terrain in an area, is conservative and biased the results in favor of higher frequencies of fog and ice.

MATCHING THE TWO MODEL PORTIONS

The plume rise model assumes a circular top-hat distribution--constant concentration throughout the plume and zero outside. The PTDIS model is a standard sector-averaged model with top-hat distributions of concentration in the horizontal and Gaussian distribution in the vertical. These two models are merged using the technique of Slawson

et al. (1). At the point of maximum rise, the plume has a circular cross section of radius R_{max}. It is then determined how far upwind a point source, whose plume grows by atmospheric turbulence, would have to be located so that its "equivalent area" would equal that of the top-hat plume. The equivalent area of the Gaussian plume is the area of the ellipse whose major axes equal 2.15 S_y and 2.15 S_z, where S_y and S_z are horizontal and vertical standard deviations of the plume. At a distance of 2.15 S, a Gaussian distribution has only 10 percent of its maximum value. Since S_y and S_z are functions of downwind distance X, the following formula is mathematically inverted for X.

$$R^2 = (2.15)^2 \, S_y(X) \, S_z(X). \qquad (1)$$

This value of X is then subtracted from the distance downwind of the point of maximum plume rise. This distance and the final height are taken as the location of the virtual origin of the plume for execution of the plume dispersion modeling.

CALCULATION OF ANTHROPOGENIC FOG AND ICE EVENTS

Using the above procedure, the concentration of water vapor at ground level is estimated every half km from 0 to 20 km, for 16 direction sectors for every hour of suitable meteorological data in the three-year record. Fog or ice is assumed to occur based on the following criteria: fog--relative humidity above 100 percent and temperature above freezing; ice--relative humidity above 100 percent and temperature below freezing.

Since the analysis for ice is similar to that for fog, the following statements about fog apply equally well for ice. It is more important when estimating the effect of anthropogenic fog to quantify the increased frequency of fog events rather than simply the number of hours of fog. If the moisture from Unit 8 scrubber causes fog at a given time, it occurs in one of two ways: (1) naturally occurring fog extended for a longer period of time or (2) fog occurring when it otherwise would not have. These two situations are considered separately. As the model is being run, four types of information are recorded at each plume impact point: the total number of anthropogenic fog events occurring sequentially with ambient fog, those not associated with ambient fog, and a similar two totals for ice. These analyses are repeated for each different plume reheat value.

APPENDIX B

THE MODEL OF AMBIENT SO_2 CONCENTRATION REDUCTION

THE MODEL OF AMBIENT SO_2 CONCENTRATION REDUCTION

The complete PTDIS model, as modified for terrain effects, was used to predict ground level SO_2 concentrations. The model was run over all hours of meteorological data and over the three reheat levels as described in Appendix A.

This procedure is significantly different from the modeling approach used in estimating anthropogenic fog and ice effects. In order to more accurately estimate ambient SO_2 reduction, plume rise was estimated directly for each hour of data without using the more involved, numerical integration plume rise estimation procedure developed by Slawson et al. (1). It was not practical to perform the numerical integration procedure for so many hours of data.